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MISSION DESIGN AND ANALYSIS FOR IRNSS-1A

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Indian Regional Navigation Satellite System (IRNSS) is a constellation of seven spacecrafts that will provide high accuracy navigation service for Indian region. This paper describes the mission design and analysis for the first in Indian Navigation s/c series, IRNSS-1A. It is positioned in geosynchronous orbit with 29 deg inclination (Non-geostationary orbit, NGSO) at 55 deg East longitude. IRNSS-1A is equipped with four reaction wheels, two star sensors and three gyroscopes. There is a 440 N Liquid Engine for orbit raising, mounted on -Roll face. There are eight 22 N engines mounted on -Roll face and two each on +Pitch and -Pitch faces. It was launched on July 1, 2013 by PSLV into a sub-synchronous transfer orbit of 284 x 20650 km with inclination of 18 deg. Launch window was determined by the target orbit RAAN requirement of 141 deg, which was selected based on limiting number of eclipse days in a year in on-orbit phase. Since the sun-orbit geometry in transfer orbit (T.O.) varies as a function of launch date, a detailed eclipse analysis was carried out for T.O. phase based on which battery charging scheme was designed by Power subsystem engineers. Also, the sun aspect angles during ascent phase were studied. For the first time, liquid engine burns (LEB) were planned with thrust vector steering driven by quaternion profile represented onboard as a polynomial. Maneuver strategies were generated for nominal, backup and contingency scenarios satisfying operational constraints and minimizing propellant expenditure. The NGSO inclination was targeted at 27 deg considering +/- 2 deg band allowed around 29 deg by the Navigation engineers, which would give us additionally over four years operational life. A five-burn strategy was planned to achieve desired drift orbit with two near-perigee burns followed by three apogee burns. The LEB orientation phases were analyzed to check for star-sensor bright light clearances and sun incidence angles on the solar arrays for power generation. Appropriate biases about the thrust direction were worked out for the cases of violation of star-sensor constraints. Range vector profiles were studied in s/c frame considering all planned orientations in T.O. phase and accurate polarization predictions were provided to the supporting ground stations. For inclination control maneuvers in on-orbit phase, usage of -Roll face thrusters were recommended after studying the effect of cross axis components when Pitch face thrusters are used. The desired target orbit of IRNSS-1A was achieved employing the nominal maneuver strategy.

1. INTRODUCTION

IRNSS is the Indian Regional Navigation Satellite System that will provide high accuracy navigation service for the Indian region. It is designed to provide accurate position information service to users in India as well as the region extending up to 1500 km from its boundary, which is its primary service area. The extended service area lies between primary service area and area enclosed by the rectangle from latitude 30 deg south to 50 deg north, longitude 30 deg east to 130 deg east. IRNSS will provide two types of services, namely, Standard Positioning Service (SPS) and Restricted Service (RS) and is expected to provide a position accuracy of better than 20m in the primary service area. IRNSS consists of a space segment and a ground segment. The IRNSS space segment consists of seven geosynchronous satellites. IRNSS ground segment is responsible for navigation parameters generation and transmission, satellite control, ranging and integrity monitoring and time keeping. IRNSS-1A, the first s/c in the series, carries two types of payloads- navigation payload and ranging payload. The navigation payload will transmit navigation service signals to the users. This payload will be operating in L5 band and S band. A highly accurate Rubidium atomic clock is part of the navigation payload of the satellite. The ranging payload consists of a C-band transponder which facilitates accurate measurement of the range of the satellite. IRNSS-1A also carries Corner Cube Retro Reflectors for laser ranging.

IRNSS-1A was launched on July 01, 2013 by PSLV-C22 from SDSC, Sriharikota. The s/c mass at lift off was 1425 kg with a propellant loading of 810.4 kg. IRNSS-1A was injected into a sub-Geosynchronous Transfer Orbit (sub-GTO) by PSLV with a 284 km perigee and 20,653 km apogee with an inclination of 18 deg with respect to the equatorial plane. The 440 N Liquid Engine (LE), mounted along negative roll axis, is used for orbit raising. The gyros are used as attitude reference during LE burns (LEB). The gyros are calibrated using star sensor attitude data. For the first time in ISRO's geosynchronous missions, LEB operation is carried out with thrust vector steering using

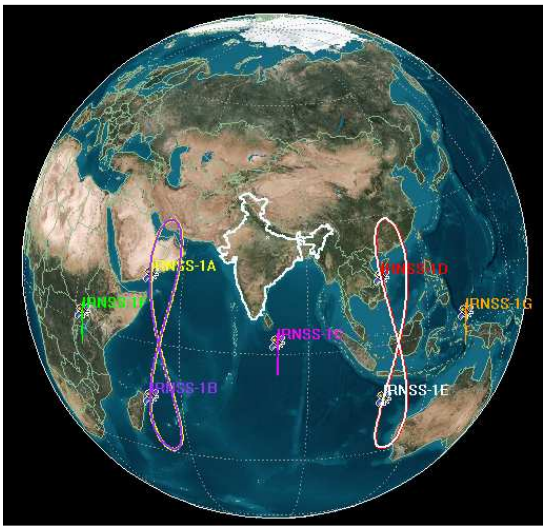
uplinked attitude steering profile (ASP). The IRNSS constellation orbit characteristics are given in Table 1 and the same is depicted in Fig. 1.

Table 1: IRNSS Constellation Characteristics

- No of spacecraft in constellation : 7
- IGSO : Inclined geosynchronous orbit
- INCL : Inclination, RAAN : Right Ascension of Ascending Node
- Longitude given in column#2 is at Equatorial Crossing for IGSO

IRNSS #	Long. (ºE)	INCL (º)	RAAN (º)
1A	55.0	29º (± 2)	135
1B	55.0	29º (± 2)	310
1C	83.0	5	274
1D	111.75	29º (± 2)	135
1E	111.75	29º (± 2)	310
1F	32.5	5	270
1G	131.5	5	270

Figure-1: IRNSS Constellation



The constellation orbit inclination and equatorial crossing longitude values were chosen by the Navigation team (NAV) to meet the user position accuracy requirements. The RAAN value is chosen for IGSO to minimize the number of days of eclipse over the mission life.

Inclination is targeted at 27 deg, at beginning of operational life (BOL), because the natural perturbation increases inclination and NAV has allowed an inclination range of 27 to 31 deg for the IGS orbit. RAAN of 141 deg is chosen at BOL of IRNSS-1A so that RAAN reaches 135 deg about a year later by which time IRNSS-1B will be launched which will also be positioned at 55 deg East with RAAN of 310 deg.

The PSLV sub-synchronous transfer orbit parameters are provided in Table 2. This paper provides the various mission analyses carried out for the IRNSS-1A NGS orbit mission covering launch window, maneuver strategies and mission profile studies.

The following are the mission analyses carried out for planning the IRNSS-1A mission:

- Launch window
- Maneuver strategy design for nominal, backup and contingency scenarios
- LEB orientation phase studies
- Mission profile studies
- Range vector profiles in s/c frame in all phases

Table-2: IRNSS-1A/PSLV-C22 Injection Parameters

Orbital Parameters at Injection	
Epoch (U T)	2013-07-01, 18:31:25.460
Perigee Height	284.0 km
Apogee Height	20652.6 km
Inclination	17.877 deg
Arg. of Perigee	178.186 deg
RAAN	142.908 deg
Mean Anomaly	4.732 deg
Orbit Period	6.1 hr

2. LAUNCH WINDOW

The launch time for IRNSS-1A mission is determined by the RAAN requirement. IRNSS-1B launch was scheduled about a year after 1A launch. The RAAN variation in IGSO phase was found to be about -6 deg/year. IRNSS-1A RAAN of 143 deg is chosen at separation from PSLV so that after all the LEBs, it reaches 141 deg. A year later, it reaches 135 deg and will be ready to be phased as desired with 1B.

The launch window was generated over the year. Launch window duration of 20 min is provided allowing for a RAAN variation of 5 deg over the window, which had been cleared by NAV team. The ascent phase sun aspect angles in s/c frame and transfer orbit phase eclipse pattern were studied as a function of the launch date and time. In the ascent phase which is of 1220 s duration, using the launch trajectory and attitude profile data provided by PSLV and considering the mounting of the s/c on PSLV, the sun aspect angle profiles with each of the s/c axes and planes were generated and studied. The results were provided to thermal sub-system for their analysis.

The sun angles with star sensor bore axes were studied and results provided to Sensor designers. Since star sensors are off during ascent phase, the bright light clearance required was specified as 20 deg from the bore axis. The Sun-to-Star sensor axis angle profiles during ascent phase for three different seasons are shown in Fig. 2, 3 & 4 respectively. For Mar 20 launch, it was found that sun comes within 20 deg of star sensor South axis from about 731 sec past lift-off for a duration of 470 sec and the minimum angle is about 11 deg which occurs at1031 sec past lift-off. For Jun 20 launch, sun comes within 20 deg of star sensor North axis from about 826 sec past lift-off till injection for a duration of 474 sec and the minimum angle is about11.8 deg which occurs at 1161 sec past lift-off. For Dec 22 launch, sun is well beyond the 20 deg limit from both star sensor axes throughout the ascent phase.

Figure-2: Sun-to-Star sensor axis angle profile during ascent phase (Mar 20)

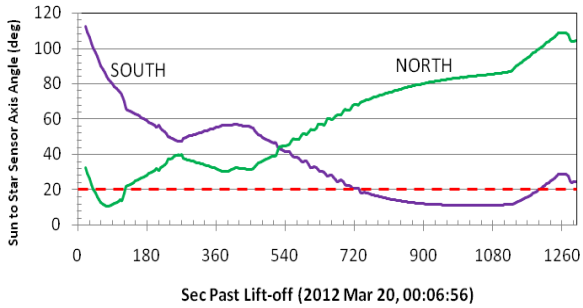


Figure-3: Sun-to-Star sensor axis angle profile during ascent phase (Jun 20)

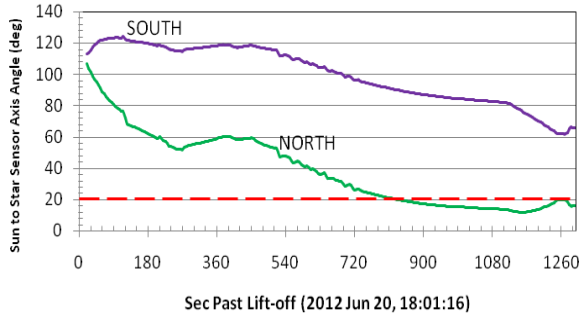
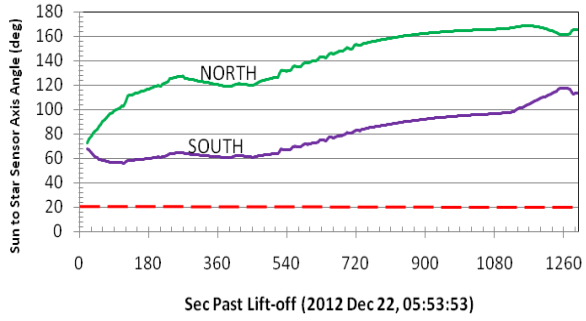


Figure-4: Sun-to-Star sensor axis angle profile during ascent phase (Dec 22)



The sun-orbit geometry varies as a function of the launch date which results in eclipse pattern variation in T.O. phase. T.O. eclipse durations for IRNSS-1A were studied over the year. The T.O. eclipse summary as a function of launch date is provided in Table 3. The maximum eclipse in T.O. phase is about 79 min for launch in last week of February. During the orbit raising phase for the end February launch, it was found that the eclipse duration increases to a maximum of 115 min in the intermediate orbits. The Power subsystem engineers designed their charging scheme based on these predictions. The star sensor bright light clearance constraint was examined during LEB maneuver orientation phases as a function of launch date. Star sensor to sun angle should be greater than 40 deg in LEB orientation. In case of any violation of this constraint, an appropriate bias is provided about the thrust direction (Roll) to clear the sensor from the sun.

The launch window for the launch period of June-July, 2013 is provided in Table 4. The sun-orbit geometry for July 1, when IRNSS-1A was launched, is shown in Fig. 5.

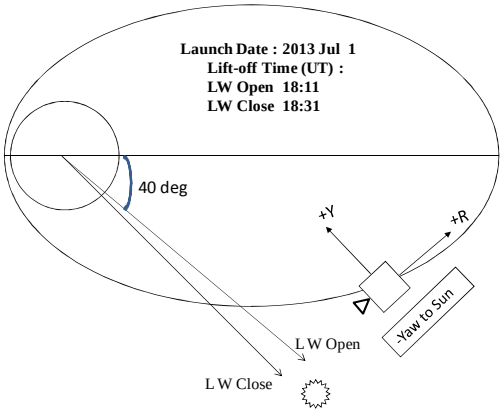
Table-3: IRNSS-1A T.O. Eclipse Summary as a Function of Launch Date

Launch Date	Sun RA (deg)	Sun Dec (deg)	T.O. Eclipse dur.(min)
Jan 30	312.1	-17.832	No Eclipse
Feb 4	317.2	-16.42	No Eclipse
Feb 7	320.2	-15.51	27.0
Feb 9	322.2	-14.89	46.0
Feb 19	332.0	-11.52	77.2
Feb 28	**341.4**	**-7.86**	**78.6**
Mar 10	350.7	-4.01	68.6
Mar 20	359.8	-0.074	54.4
Mar 30	9.8	4.23	39.4
May 9	47.2	17.641	23.22
Jun 20	89.8	23.436	22.24
Aug 7	138.0	16.182	23.75
Sep 20	178.1	0.815	26.74
Nov 15	231.0	-18.620	16.00
Dec 22	270.9	-23.433	No Eclipse

Table-4: IRNSS-1A Launch Window

DATE	LW OPEN (UT at LIFT-OFF)	LW CLOSE	DUR. (MIN)
JUN 01	20:10	20:30	20
JUN 05	19:54	20:14	20
JUN 10	19:35	19:55	20
JUN 15	19:15	19:35	20
JUN 20	18:56	19:16	20
JUN 25	18:36	18:56	20
JUL 01	18:11	18:31	20
JUL 05	17:57	18:17	20
JUL 10	17:37	17:57	20
JUL 15	17:17	17:37	20
JUL 20	16:58	17:18	20
JUL 25	16:38	16:58	20
JUL 30	16:18	16:38	20
JUL 31	16:14	16:34	20

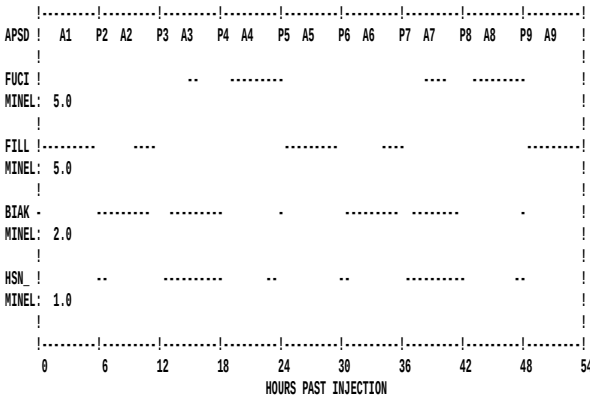
Figure-5: Sun-Orbit geometry and spacecraft orientation



3. TRANSFER ORBIT EVENTS

The ground station network comprises Hassan (HSN) which is the Control Center, Biak in Indonesia which is also an ISRO station and two external stations - Fillmore (FILL) in US and Fucino (FCNO) in Italy. For launch on 2013 July 1 with lift-off at 18:11 UT, the s/c is in eclipse for about 63 seconds after injection. In each of the later T.O.'s the s/c will be in eclipse for about 22 min around perigee. The sub-synchronous T.O. visibility chart for the considered ground stations is provided in Fig. 6 for nine T.O.'s. Biak visibility exists for 4 min from separation. Fillmore AOS occurs nearly 30 min after separation and it supports T.O.-1 operations. T.O.-2 is supported mainly by Biak and Fillmore with a short visibility of 20 min for Hassan in the perigee arc. T.O. -3 is supported mainly by Hassan and Biak. T.O.-4 is supported mainly by Fucino with short visibilities for Hassan and Biak in perigee arc. The elevation profiles for first four T.O.'s are shown in Fig. 7.

Figure-6: T.O. Visibility Chart



The operationally optimal maneuver strategy designed for acquiring the desired IGSO from the sub-GTO is a 5-burn strategy with two near perigee burns followed by three apogee burns. The perigee longitudes are shown in Table 5. Perigee#5 and Perigee#9 longitudes are relatively close to Biak and these are the nominal and backup near-perigee burn opportunities. Biak visibility near Perigee#5 starts about 14 sec before perigee crossing and lasts for about 10 min.

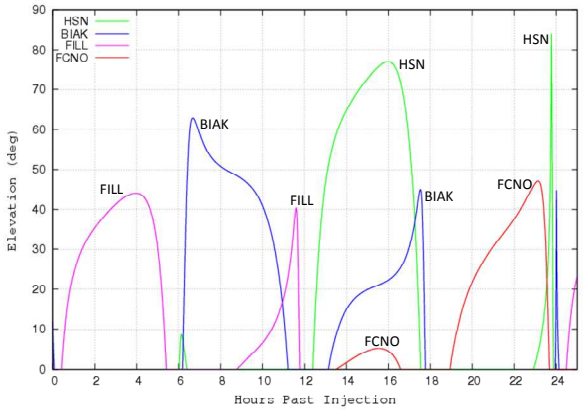
Table 5: Perigee Longitudes for Sub-synchronous T.O.

Perigee No.	Longitude (deg East)
2	34.0
3	303.6
4	213.1
5	***122.7***
6	32.2
7	301.7
8	211.3
9	***120.8***
10	30.4

A perigee burn rehearsal was planned in the 20 min visibility period of Hassan in T.O.-2, which starts 7 min after PRG#2 crossing. The LEB rehearsal mainly involved exercising the command sequence for LEB and following the attitude steering profile without thrusters firing.

The range vector direction in the s/c frame (Az-El) was generated for all phases and results were provided to communications engineers for appropriate ground station polarization setting.

Figure-7: Elevation Profiles (T.O.1,2,3,4)



4. MANEUVER STRATEGY TO ACHIEVE TARGET ORBIT

The objective of the maneuver strategy is to achieve the desired drift orbit satisfying the mission constraints and minimizing the propellant expenditure. Since IRNSS-1A is put into a sub-GTO, the optimal strategy is to first perform an in-plane maneuver at perigee to raise the T.O. apogee to synchronous level and then perform combined maneuvers at the synchronous apogee to achieve the desired drift orbit with the desired inclination. The perigee burn opportunities were examined considering ground station visibility requirement for monitoring the burn. It was found that adequate visibility was not available around perigee crossings to have the burn centered on Perigee. Mission put a constraint that every Liquid Engine Burn had to be with ground station visibility.

The following maneuver strategy was proposed considering the Mission constraint of fully monitoring each LEB:

- Operationally Optimal Strategy: Two Near-perigee burns around Perigee#5 and Perigee#8 with single station visibility during the burn and three apogee burns with dual station visibility

The target drift orbit inclination was chosen as 27 deg to minimize the inclination correction in the apogee maneuvers. Since the IGSO RAAN was 141 deg, the luni-solar gravitational perturbations increase the inclination. The inclination control strategy proposed was to achieve 27 deg at beginning of life, allow it to naturally build up to 29 deg and then use the available propellant to maintain the inclination around 29 deg. After using up the available propellant, allow the inclination to further naturally increase up to 31 deg. This way, the s/c operational life is enhanced over 5 years.

The following maneuver strategies are designed and analyzed:

- Nominal & backup strategies
- Maneuver strategy for T.O. with worst case launch dispersions
- Contingency scenarios:
  - A near full burn at Apogee-1 if a leak is observed after separation from the launch vehicle in the Liquid Engine line.
  - A large first burn is required in case of a propulsion contingency after Latch Valve Gas side (LVG) open before apogee#4
  - If a leak is observed in the propulsion system over the course of maneuver#1 (MVR#1), then Liquid Apogee Motor (LAM) burn has to be completed within next 14 hours

4.1 Nominal Maneuver Strategy

The operationally optimal nominal maneuver strategy is a 5-burn strategy with two near-perigee burns and three apogee burns. Two near-perigee burns are planned to raise the T.O. apogee to synchronous level. The first burn is carried out post-perigee#5 and is fully supported by Biak. The elevation profile for network stations around perigee#5 is shown in Fig 8. Biak visibility starts about 1 min before burn start and its elevation is about 8.5 deg at the time of burn start and about 4.6 deg at burn end. The nominal maneuver strategy is summarized in Table 6. MVR#1 starts in eclipse. Eclipse starts about 17 min before the burn and ends 5.2 min after burn start. The last 2.4 min of the 7.7 min burn is sunlit. The post-maneuver#1 elevation profiles for the ground stations are shown in Fig. 9.

The second burn is carried out pre-perigee#8 and is supported by Hassan and Biak. The elevation profile for network stations around perigee#8 is shown in Fig 10. Hassan elevation at burn start is about 24 deg and Hassan LOS is over 3.5 min after burn start. Biak AOS occurs about 56 sec after burn start and its elevation is about 6 deg at the time of Hassan LOS and about 8.7 deg at burn end. The MVR#2 full burn duration of 12.3 min is in eclipse. Eclipse starts 1.7 min before burn start and ends 7.8 min after burn end. The delta-V imparted in the perigee burns is about 388.7 m/s. The propellant consumed is about 169.4 kg. The total perigee burn duration is about 1197 sec. The post-maneuver#2 elevation profiles for the ground stations are shown in Fig. 11.

Three more burns are planned at apogees 9, 11 and 12 respectively to achieve the desired drift orbit. After MVR#4, the s/c is continuously visible to Hassan. After MVR#5 at 44.5 deg East longitude, which is 10.5 deg west of the slot, the inclination achieved is 27 deg and the longitude drift rate is about 1.7 deg/rev.

The time taken for drift orbit acquisition is nearly 5 days from launch. The delta-V required for station acquisition is 5.5 m/s and corresponding propellant expenditure is 1.5 kg. The total delta-V for achieving

the desired IGS orbit is about 1893.9 m/s and the corresponding propellant requirement is 655.5 kg.

For the on-orbit inclination control maneuvers, it was found that, using the north/south thrusters resulted in significant cross components disturbing the longitude drift because of the –Roll thrusters coming on for attitude control. The s/c has no thrusters mounted on the + Roll side because atomic clocks and star sensors are located on this side. Therefore, it was suggested to mission to employ only West (-Roll) thrusters for NSSK maneuvers.

Table-6: Nominal Maneuver Strategy

S/C Mass	LE Thrust	LE Isp
1425.0 kg	433.200 N	314.200 sec

MVR No.	APG/ PRG No.	Burn %	Delta-V (m/s)	Burn Start Time (UT)	Burn Dur. (sec)	Prop. (kg)
1	PRG-5	-	143.6	2013-07-02,18:33	460.0	65.1
2	PRG-8	-	245.1	2013-07-03,16:05	737.2	104.3
3	APG-9	54.0	810.0	2013-07-04,07:53	2059.2	290.9
4	APG-11	40.9	613.1	2013-07-05,13:05	1239.9	174.3
5	APG-12	5.1	76.6	2013-07-06,11:24	138.3	19.4
TOTALS			1888.4		4634.6	654.0
ORBITAL CHARACTERISTICS						
	PRG. ALT.	APG. ALT.	INCL. (deg)	RAAN (deg)	Long (deg)	Long. Drift (deg/rev)	Period (hrs)
PRE MVR1	283.9	20667.4	17.87	142.1	125.8	269.02	6.049
POST MVR1	295.7	25097.0	17.87	142.1	159.1	250.46	7.283
POST MVR2	342.9	35964.7	17.88	141.5	147.5	200.23	10.622
POST MVR3	11936	35799.5	24.18	141.2	94.5	141.28	14.541
POST MVR4	31637.1	35804.8	26.75	141.2	17.9	26.12	22.198
POST MVR5	35501.9	35804.9	27.00	141.2	44.5	1.70	23.822

Figure-8: Elevation Profiles Around MVR#1 (PRG#5)

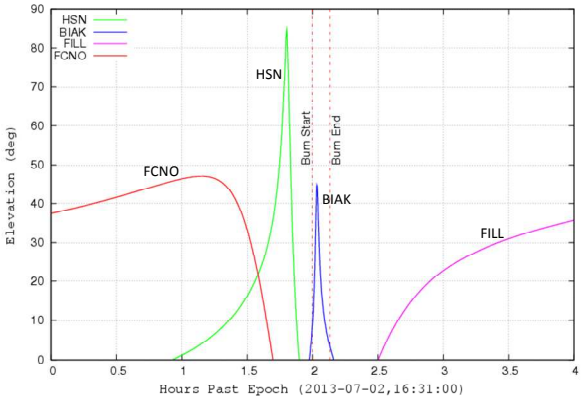


Figure-9: Elevation Profiles Post MVR#1

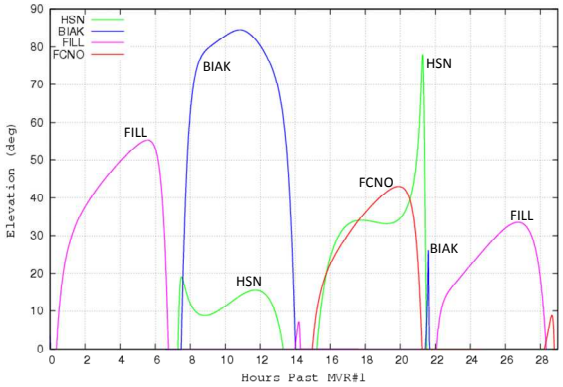


Figure-10: Elevation Profiles Around MVR#2 (PRG#8)

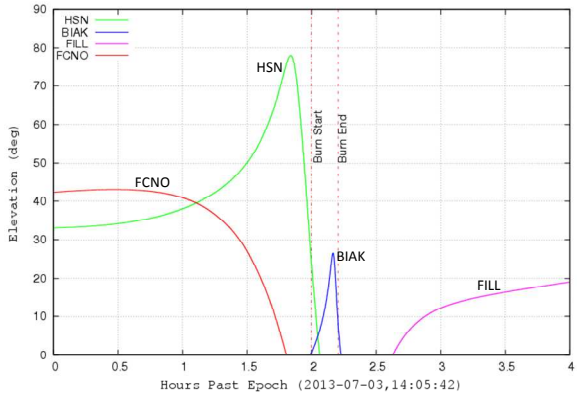
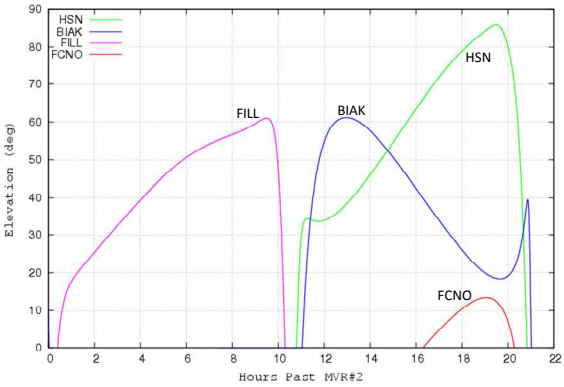


Figure-11: Elevation Profiles Post MVR#2



4.2 Spacecraft Orientation in Liquid Engine Burns

All the LEBs are carried out with Attitude Steering Profile (ASP) to improve the efficiency of the maneuver. The thruster configuration is shown in Fig. 12. The main Liquid Engine is mounted on –Roll side and the thrust direction is along +Roll. The s/c orientation during MVR#1 (Post-PRG#5) is depicted in Fig. 13. The ASP includes a 65 deg roll bias to satisfy the star sensor bright light clearance of 40 deg from the sun. The solar panel normal is along +Roll in MVR#1

phase to enable power generation outside eclipse period. The panel normal to sun angle profile in MVR#1 phase along with eclipse region indication, is shown in Fig. 14. It varies from 50 deg to 46 deg from eclipse exit to end of burn. The Sun to star sensors angles profile in MVR#1 phase incorporating 65 deg roll bias, are shown in Fig. 15 &16 respectively.

Figure-12: Thrusters Configuration

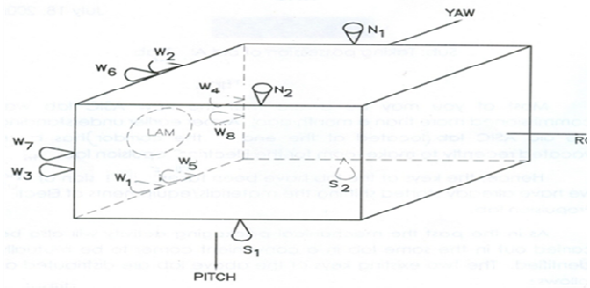


Figure-13: Post-PRG#5 Spacecraft Orientation (MVR#1)

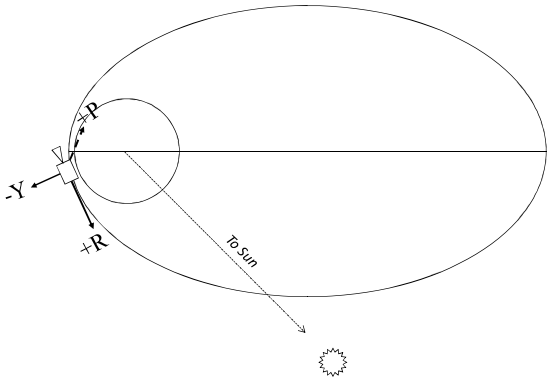


Figure-14: Sun to Panel Normal Angle Profile (MVR#1)

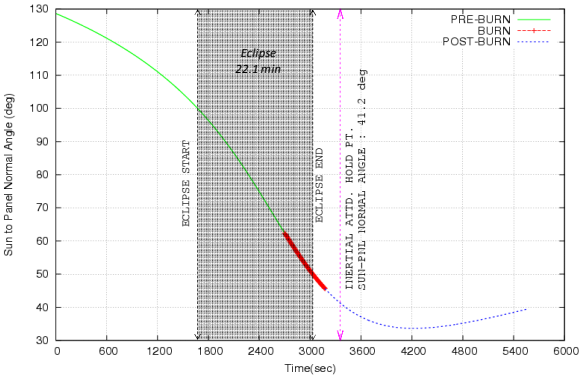


Figure-15: Sun to SS-1 Angle Profile (MVR#1)

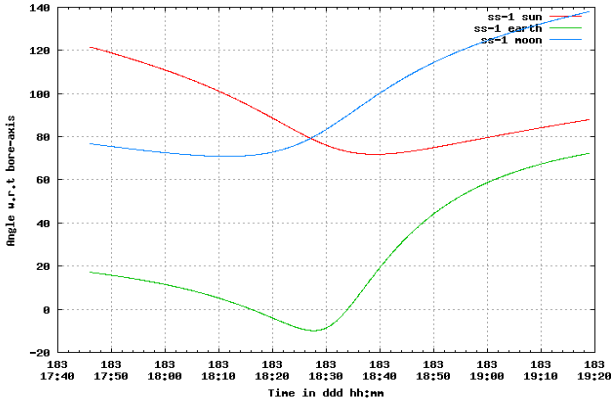
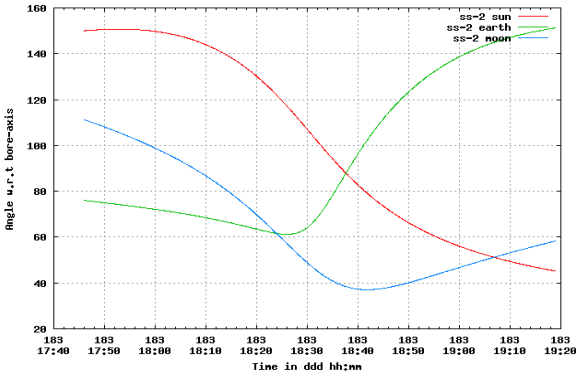


Figure-16: Sun to SS-2 Angle Profile (MVR#1)



The s/c orientation during MVR#2 (Pre-PRG#8) is depicted in Fig. 17. In this case also, the ASP includes a 65 deg roll bias to satisfy the star sensor bright light clearance of 40 deg from the sun. The solar panel normal is maintained along +Roll in MVR#2 phase. The panel normal to sun angle profile in MVR#2 phase along with eclipse region indication, is shown in Fig. 18. It is about 51 deg after eclipse exit which occurs about 7.8 min after burn end. The Sun to star sensors angles profile in MVR#2 are shown in Fig. 19 &20 respectively.

The s/c orientation during MVR#3 (APG#9) is depicted in Fig. 21. In the apogee maneuver case, the sun is in the –Yaw to –Roll quadrant. Therefore, the solar panel normal is maintained along –Roll for power generation in apogee maneuver phase. The panel normal to sun angle profile in MVR#3 phase is shown in Fig. 22. It varies from 79.5 deg to 75.5 deg over the burn duration. The sun to star sensors axes angle profiles in MVR#3 phase are shown in Fig. 23 & 24 respectively. They are well above the specified minimum value of 40 deg.

Figure-17: Pre-PRG#8 Spacecraft Orientation (MVR#2)

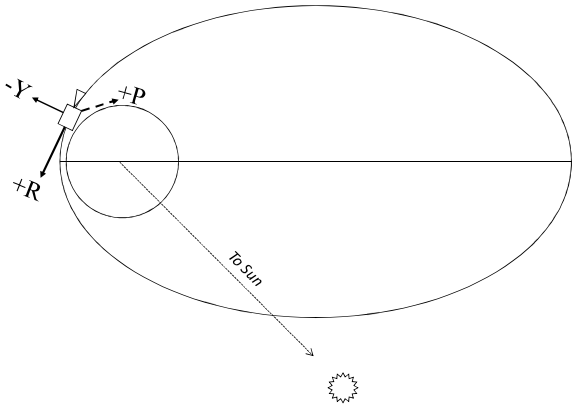


Figure-18: Sun to Panel Normal Angle Profile (MVR#2)

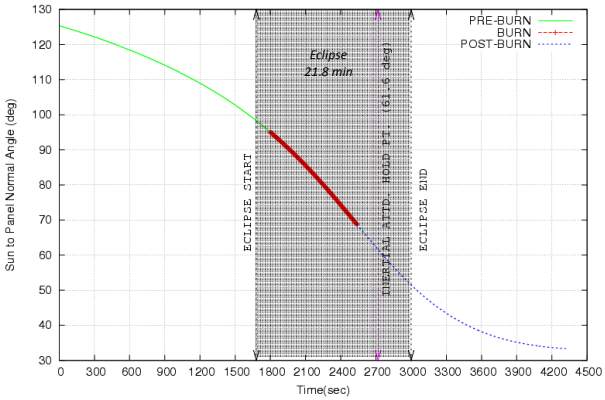


Figure-19: Sun to SS-1 Angle Profile (MVR#2)

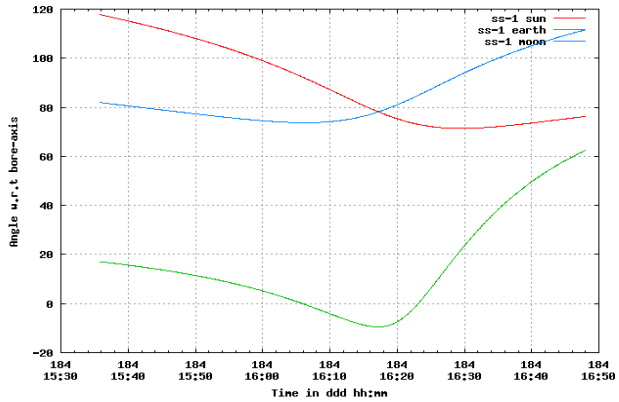


Figure-20: Sun to SS-2 Angle Profile (MVR#2)

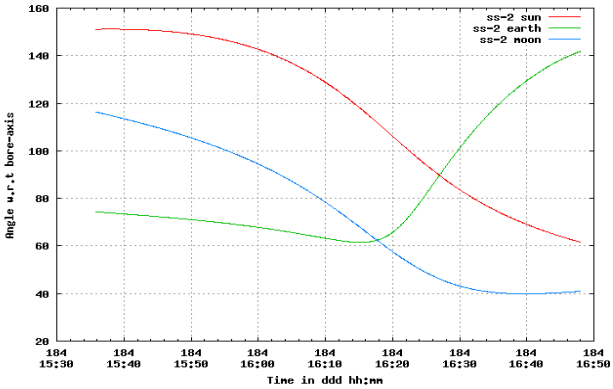


Figure-21: Apogee Maneuver Orientation (MVR#3)

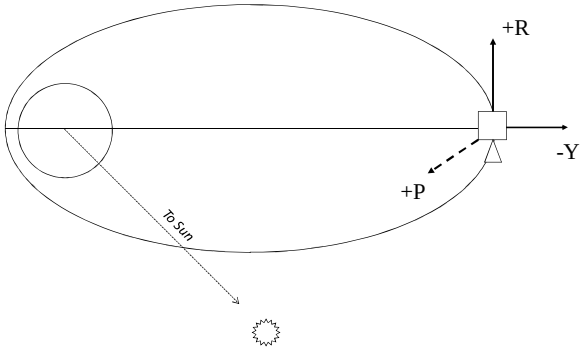


Figure-22: Sun to Panel Normal Angle Profile (MVR#3)

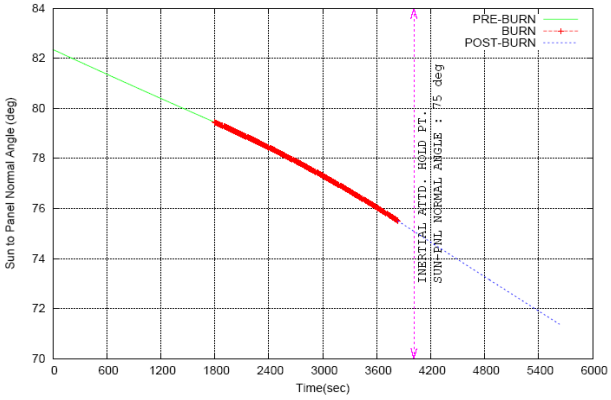


Figure-23: Sun to SS-1 Angle Profile (MVR#3)

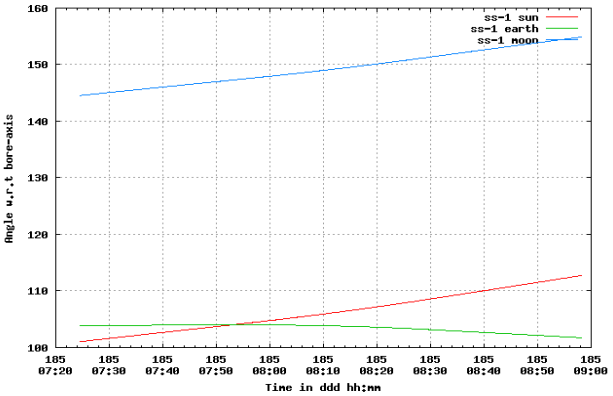
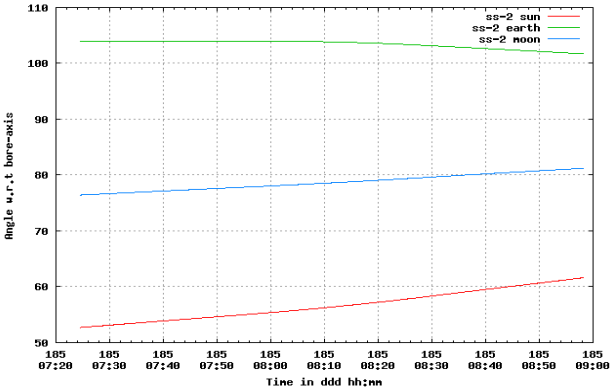


Figure-24: Sun to SS-2 Angle Profile (MVR#3)



4.3 Backup Maneuver Strategy

The backup maneuver strategy is summarized in Table 7. If the first near-perigee burn opportunity at perigee#5 is missed, then next opportunity is near perigee#9. Two near-perigee burns are planned to raise the T.O. apogee to synchronous level. The first burn is carried out post-perigee#9 and is fully supported by Biak. The second burn is carried out pre-perigee#12 and is supported by Hassan and Biak. The delta-v imparted in the perigee burns is 387.4 m/s. The propellant consumed is 169.4 kg. The total perigee burn duration is about 1190 sec.

Three more burns are planned at apogees 13, 15 and 16 respectively to achieve the desired drift orbit. The time taken for drift orbit acquisition is nearly 6 days from launch. The total delta-v for achieving desired NGSO is about 1892.9 m/s and the corresponding propellant requirement is 656.9 kg.

Table-7: Backup Maneuver Strategy

MVR No.	APG/ PRG No.	Burn %	Delta-V (m/s)	Burn Start Time (UT)	Burn Dur. (sec)	Prop. (kg)
1	PRG#9	-	144.0	2013-07-03,20:00	460.0	65.5
2	PRG#12	-	243.4	2013-07-04,17:33	729.7	103.9
3	APG#13	53.4	801.2	2013-07-05,09:19	2030.7	289.2
4	APG#15	41.6	623.8	2013-07-06,14:22	1264.6	177.8
5	APG#16	5.0	75.0	2013-07-07,12:46	135.5	19.0
TOTALS			1887.4		4620.5	655.4

ORBITAL CHARACTERISTICS							
	PRG. ALT.	APG. ALT.	INCL. (deg)	RAAN (deg)	Long (deg)	Long. Drift (deg/rev)	Period (hrs)
PRE MVR1	282.6	20674.8	17.88	141.5	125.8	268.99	6.05
POST MVR1	296.4	25099.5	17.87	141.4	158.8	250.45	7.284
POST MVR2	338.0	35966.9	17.88	140.9	147.4	200.25	10.621
POST MVR3	11740.5	35799.8	24.14	141.0	92.6	142.34	14.471
POST MVR4	31711.5	35805	26.76	141.1	18.1	25.66	22.229
POST MVR5	35501.9	35805.1	27.0	141.1	44.1	1.70	23.822

4.4 Maneuver Strategy for 3-sigma low T.O.

The worst case 3-sigma low T.O. is constructed with the apogee, perigee and inclination values reduced by the specified dispersion and with higher separation between apsidal and nodal lines. The PSLV launch dispersions are given in Table 8. Perigee#5 and Perigee#9 longitudes are relatively close to Biak and these are the near-perigee burn opportunities. Biak visibility near Perigee 5 starts about 3.5 min before perigee crossing and lasts for over 9 min.

Table-8: PSLV 3-sigma Dispersions

Dispersions		
Perigee height	(km)	± 5
Apogee Height	(km)	± 675
Inclination	(deg)	± 0.2
Argument of Perigee	(deg)	± 0.2

The Maneuver Strategy for 3-sigma low T.O. is summarized in Table 9. The first three burns are perigee burns with first burn almost centered on perigee#5 and next two are near-perigee burns carried out pre-perigee#9 and post-perigee#13. Maneuver#1 is supported by Biak and next two burns are supported by Hassan. The delta-v imparted in the perigee burns is

about 402 m/s. The propellant consumed is about 175 kg. The burn duration is about 1232 sec.

Three more burns are planned at apogees 15, 17 and 18 respectively to achieve the desired drift orbit. The time taken for drift orbit acquisition is nearly 7 days from launch. The total delta-v for achieving desired NGS orbit is about 1913 m/s and the corresponding propellant requirement is about 662 kg. The penalty in delta-v, as compared to the nominal strategy for expected nominal T.O. case, is nearly 19 m/s and that in propellant is about 6.6 kg.

Table-9: Maneuver Strategy for 3-sigma low T.O.

MVR No.	APG/ PRG No.	Burn %	Delta-V (m/s)	Burn Start Time (UT)	Burn Dur. (sec)	Prop. (kg)
1	POST-PRG#5	-	112.1	2013-07 02,19:07	360.0	51.3
2	PRE-PRG#9	-	186.4	2013-07-03, 21:57	570.0	81.2
3	POST-PRG#14	-	103.6	2013-07-05, 18:08	302.1	43.0
4	APG#15	51.1	769.5	2013-07-06, 09:47	1950.6	277.8
5	APG#17	43.9	660.8	2013-07-07, 14:16	1338.9	188.3
6	APG#18	5.0	75.3	2013-07-08, 12:40	135.1	19.0
TOTALS			1907.7		4656.7	660.6
ORBITAL CHARACTERISTICS						
	PRG. ALT.	APG. ALT.	INCL. (deg)	RAAN (deg)	Long (deg)	Long. Drift (deg/rev)	Period (hrs)
PRE MVR1	278.1	19997.4	17.67	142.2	124.8	271.74	5.868
POST MVR1	280.0	23295.0	17.67	142.2	152.0	258.19	6.768
POST MVR2	297.9	30437.5	17.68	141.5	85.5	226.66	8.865
POST MVR3	301.9	35965.8	17.68	140.6	139.7	200.4	10.609
POST MVR4	10980.5	35793.5	23.89	140.7	84.5	146.47	14.196
POST MVR5	31704.5	35799.5	26.75	140.8	18.3	25.73	22.224
POST MVR6	35506.9	35799.7	27.0	140.8	44.3	1.70	23.822

4.5 Contingency Maneuver at Apogee#1

In case of a propulsion contingency, a full burn may have to be carried out at apogee-1. The s/c is visible only to Fillmore in T.O.-1. The longitude at apogee-1 is about 259 deg East. The parking slot of 55 deg East is 156 deg east of the apogee-1 longitude.

A single LAM burn is planned around the sub-synchronous apogee-1 to raise the perigee to synchronous level and also achieve inclination of 27 deg. This results in a longitude drift rate of about 91 deg/rev so that the s/c will be at about 42 deg East one and half revolutions later. The plan is summarized in Table-10.

It is assumed that LAM is not usable for the second burn. The second burn has to be carried out using the four 22 N West thrusters, mounted on –Roll face and normally used for attitude control during LAM firing, in backup LAM mode. The delta-V imparted in the second burn is about 346 m/s. The West thrusters firing duration is about 1457 sec and the propellant consumed is 90.2 kg. The total delta-V for achieving target NGS orbit is 2259 m/s and the corresponding total fuel is nearly 753 kg. The penalty in delta-V and propellant consumed with respect to nominal plan is 365 m/s and 97.5 kg respectively.

Table-10: Contingency Single LEB Strategy at APG-1

LAM/ WEST	APG No.	Delta-V (m/s)	Burn Duration (sec)	Prop. (kg)
LAM	1	1906.9	4640.0	660.7
WEST	3	346.2	1456.9	90.2
TOTALS		2253.1	6096.9	750.9
ORBITAL CHARACTERISTICS				
	PRG. ALT.	APG. ALT.	INCL. (deg)	RAAN (deg)	Long (deg)	Long. Drift (deg/rev)	Period (hrs)
PRE AMF1	288.1	20582.4	17.87	142.9	257.1	269.35	6.027
POST AMF1	20821.3	35785.2	27.0	142.9	267.1	91.44	17.855
POST AMF2	35472.6	35788.1	27.0	142.8	42.0	2.00	23.802

4.6 Contingency Maneuver at Apogee#4

IRNSS-1A has a liquid bi-propellant propulsion system and all the LAM firings are planned in pressure regulated mode. The Latch Valve Gas (LVG) side is opened before Apogee#4 to pressurise the propellant tanks, though the first LAM burn is post-Perigee#5. This is to take care of pressure regulator related contingencies. A large first burn is required at Apogee#4 in case of pressure regulator failure after LVG open, to reduce the propellant tank pressures to safe levels. The strategy with MVR-1 at apogee-4 is summarized in Table-11. The delta-V imparted in the first burn is about 1453 m/s and the propellant consumed is 538.5 kg. The burn duration is about 3782 sec. The post-MVR#1 drift rate achieved is about 184 deg/rev and the target inclination of 27 deg is achieved. Second burn is planned at apogee-7, through this maneuver perigee will be corrected fully to the synchronous height. The post-MVR#2 drift rate is about 92 deg/rev. Remaining correction is planned at Apogee-10. The total delta-V for achieving NGS orbit is about 2270 m/s and the corresponding total propellant is nearly 746 kg. The penalty in deltav and propellant consumed with respect to nominal plan is 376 m/s and 91 kg respectively.

Table-11: Contingency Single LEB Strategy at APG-4

MVR No.	APG No.	Delta-V (m/s)	Burn Duration (sec)	Prop. (kg)
1	4	1452.7	3781.5	538.5
2	7	463.9	875.6	124.7
3	10	350.2	578.4	82.4
TOTALS		2266.8	5235.5	745.6

ORBITAL CHARACTERISTICS							
	PRG. ALT.	APG. ALT.	INCL. (deg)	RAAN (deg)	Long (deg)	Long. Drift (deg/rev)	Period (hrs)
PRE MVR1	287.7	20582.4	17.87	142.3	345.9	269.35	6.027
POST MVR1	18897.3	20765.8	27.0	142.1	352.7	183.57	11.73
POST MVR2	20770.1	35785.4	27.0	142.0	179.7	91.74	17.835
POST MVR3	35615.1	35780.2	27.0	141.9	47.5	1.13	23.859

4.7 Contingency Maneuver at Apogee#6

If a leak is observed in the propulsion system over the course of MVR-1, then LAM burn has to be completed within next 14 hours. This plan is summarized in Table-12. The second LAM burn is planned at the sub-synchronous apogee#6 to raise perigee to synchronous level and achieve inclination of 27 deg. The third and last LE burn is planned at apogee#10 using West thrusters in backup plan mode to impart 213 m/s delta-v. The total delta-V for achieving GSO is about 2142 m/s and the corresponding total propellant is nearly 723 kg. The penalty in delta-V and propellant consumed with respect to nominal plan is about 248 m/s and 68 kg respectively.

Table-12: Contingency Single LEB Strategy at APG-6

MVR No.	APG/ PRG No.	Delta-V (m/s)	Burn Duration (sec)	Prop. (kg)
1	POST-PRG#5	144.0	460.0	65.5
2	APG-6	1766.9	4187.1	596.3
3*	APG-10	212.8	916.0	56.7
TOTALS		2123.7	5563.1	718.5

ORBITAL CHARACTERISTICS							
	PRG. ALT.	APG. ALT.	INCL. (deg)	RAAN (deg)	Long (deg)	Long. Drift (deg/rev)	Period (hrs)
PRE AMF1	282.9	20675.6	17.87	142.3	125.9	268.99	6.051
POST AMF1	295.2	25120.0	17.87	142.2	159.1	250.36	7.289
PRE AMF2	25133.7	35785.9	27.0	142.7	143.1	66.01	19.546
POST AMF3	34805.4	35785.2	27.0	142.6	14.6	6.26	23.518

* West Thrusters

5.0 Maneuver Strategy Realization

Based on the carried out detailed mission analysis the 5-burn operationally optimal maneuver strategy was successfully implemented for the orbit raising of IRNSS-1A. The launch dispersions were well within the quoted dispersions from PSLV. The planned and realized delta-V, thrust and observed yaw error for each burn are shown in Table 12 & Table 13.

Table-12: Realized delta-V and burn durartion

MVR No.	PRG/APG No.	Burn %	Burn Dur. (sec)	Delta-V (m/s)		
				Expected	Realized	Diff.
1	PRG-5	-	475.04	145.73	146.11	0.38
2	PRG-8	-	738.24	243.76	244.85	1.09
3	APG-9	53.4	2019.0	806.17	799.76	-6.41
4	APG-11	41.8	1248.0	626.56	626.41	-0.15
5	APG-12	4.8	126.56	70.55	71.91	1.36
Totals			4780.3		2003.02	

Table-13: Realized Thrust

MVR No.	PRG/APG No.	Thrust (N)			Yaw Error (deg)
		Expected	Realized	Diff.	
1	PRG-5	425.0	426.09	1.09	-
2	PRG-8	428.5	430.36	1.86	-
3	APG-9	437.52	434.45	-3.07	0.17
4	APG-11	434.68	434.58	-0.10	0.19
5	APG-12	428.82	437.09	8.27	0.10

6.0 Conclusion

All the mission design and analysis aspects for the first navigation spacecraft mission of India, IRNSS-1A, are covered in this paper. The launch window analysis involving launch times and sun aspect angle studies are described. Maneuver strategies for nominal, backup and contingency scenarios are provided. The spacecraft orientation analysis in the LEB phases is described. The IRNSS-1A mission successfully accomplished combined optimization of launch vehicle and satellite capabilities to maximize the operational life of the s/c. The estimated operational life is more than 12 years which was realized through the operationally optimal maneuver strategy selected from the detailed mission analysis and appropriate selection of target inclination.

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